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PREDICTIVE SENSOR METHOD AND APPARATUS

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ABSTRACT

A microprocessor and electronics package employing predictive methodology was developed to accelerate the response time of slowly responding hydrogen sensors. The system developed improved sensor response time from approximately 90 seconds to 8.5 seconds. The microprocessor works in real-time providing accurate hydrogen concentration corrected for fluctuations in sensor output resulting from changes in atmospheric pressure and temperature. Following the successful development of the hydrogen sensor system, the system and predictive methodology was adapted to a commercial medical thermometer probe. Results of the experiment indicate that, with some customization of hardware and software, response time improvements are possible for medical thermometers as well as other slowly responding sensors.

INTRODUCTION

John C. Stennis Space Center (SSC) is NASA's "Center of Excellence" for large rocket engine ground testing. In the course of certifying the Space Shuttle Main Engine (SSME) for flight readiness and conducting engine improvement research and development, SSC consumes 10 million pounds of hydrogen each year. To transport, store, and supply hydrogen for testing, SSC utilizes an extensive system of tank trucks, barges, storage tanks, pumps, and transfer lines. While most of the hydrogen is handled in liquid form through cryogenic storage vessels and vacuum jacketed piping, some hydrogen is also converted to the gaseous state prior to use.

Compounding the variety of hydrogen storage and handling problems found at SSC are a wide range of environmental conditions which make monitoring for leaks particularly difficult. Temperature can vary from rather high, due to the near tropical summers of south Mississippi, to very low, due to leakage of liquid hydrogen. Pressure can vary fairly dramatically in areas near the rocket engines due to overpressure or drawdown effects during engine tests. In some facility areas, inert "purge" gases are used to minimize the possibility of hydrogen ignition in the event of leakage. In the dynamic environment of test operations, dramatic changes in these variable conditions can occur at any time.

The potential for severe damage or injury resulting from the ignition of leaking hydrogen prompted NASA to pursue development of a fast, rugged and reliable hydrogen leak sensor capable of providing accurate results through a wide range of rapidly changing environmental conditions. Although a commercial sensor was available with good ruggedness and immunity to interferences, the sensor responded slowly and exhibited non-linearities with fluctuations in temperature and pressure. A predictive sensor method and apparatus was developed to obtain the fastest possible response time while taking advantage of the slow sensor's more desirable characteristics. The concept was implemented using a commercially available microcontroller to: 1) acquire data from hydrogen, temperature, and pressure

sensors, 2) process the predictive algorithm, and 3) linearize the output for the measured fluctuations in temperature and pressure. The success of this method stimulated further investigations of other applications involving slow sensors to determine the suitability of the predictive sensor method and apparatus for commercial development.

PREDICTIVE SENSOR METHODOLOGY AND SYSTEM DEVELOPMENT

To varying degrees, most sensors exhibit responses which lag behind the input eliciting the response. In conventional measurement systems, this lag is carried through and registered in the systems output device. A diagram of the conventional measurement process is shown in Figure 1. In many applications a lagging response is tolerable. In some cases however, a very rapid or near-real time response may be critical. In such cases, the measurer may be tempted to trade-off other desirable sensor features such as linearity, repeatability, ruggedness, or cost in order to achieve the desired speed of response. With the predictive sensor method and apparatus, the desirable characteristics inherent to the slow sensor are maintained while response time is dramatically improved. An illustration of the predictive sensor method and apparatus is provided in Fig. 2.

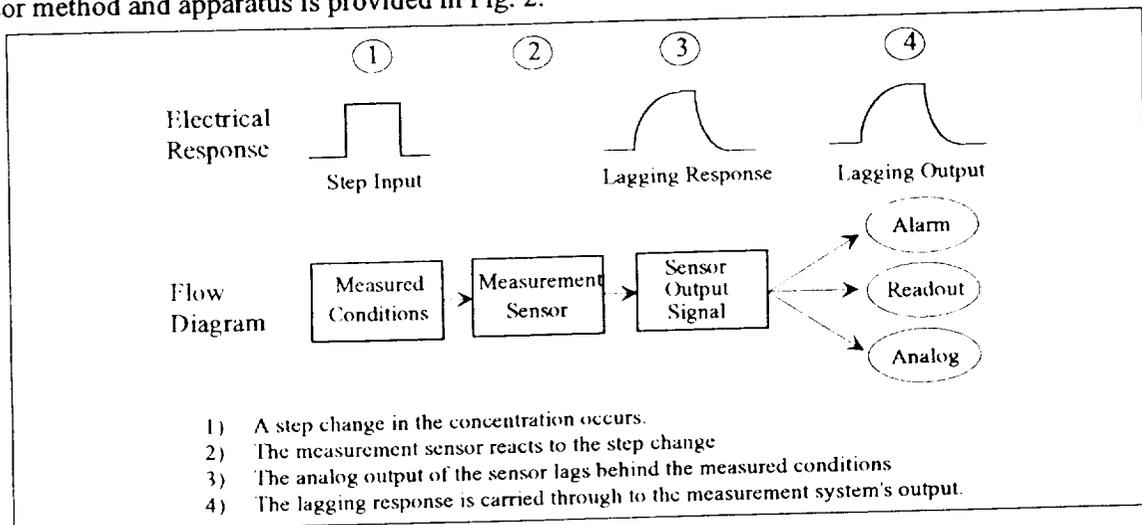


Figure 1. Illustration of Lagging Response in Conventional Measurement Systems

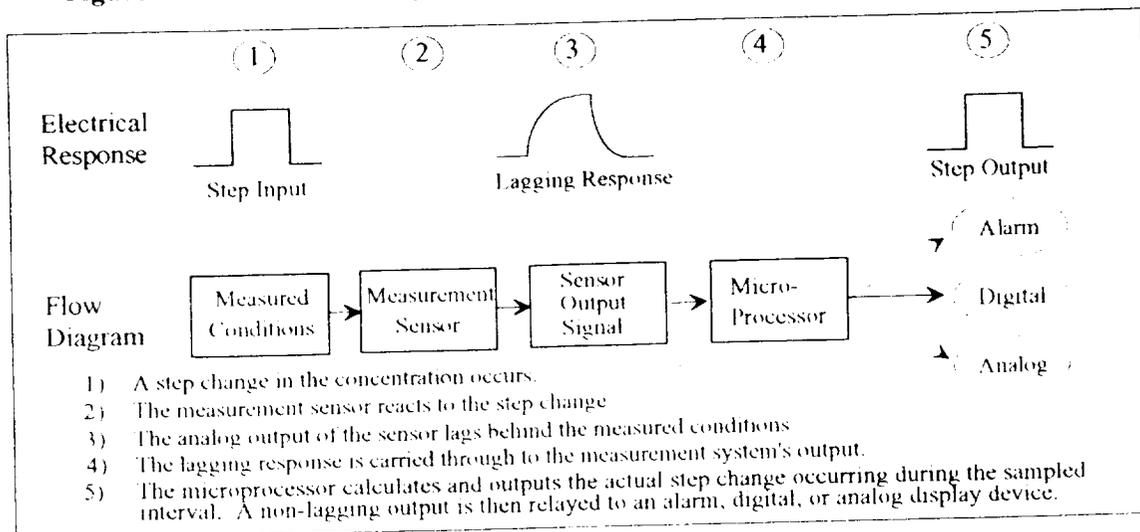


Figure 2. Illustration of Predictive Sensor Method and Apparatus

The slow responding hydrogen sensor, for which this method was developed, is an electrochemical sensor originally designed for service in nuclear power plant containment vessels. With the exception of response speed the sensor's construction for extreme ruggedness, high reliability, and good accuracy, make the sensor ideally suited for NASA service. The sensor is comprised of a semi-solid electrolyte with a platinum black sensing electrode and platinum reference electrode. The sensing electrode sits behind a polymer membrane which is selectively permeable to hydrogen. The selective permeability of the membrane is the reason for the sensor's good rejection of gases which typically interfere with the accuracy of electrochemical sensors. However, the selective permeability of the membrane is also the primary cause for the sensor's lagging response. Specifically, the hydrogen molecules diffuse through the membrane at a temperature dependent rate thus limiting the rate which the hydrogen enters the electrochemical cell and causes a change in potential between the sensing and reference electrodes.

Hardware and Software Implementation

An analysis of the lagging process led to the development of a mathematical model. After some refinement using spreadsheet analysis, the model was implemented for near-real time estimation of hydrogen concentration and linearization for fluctuations in temperature and pressure. The model was initially coded and tested in the C language. The code was later converted to BASIC and implemented in microcontroller firmware. Ultimately, a compact system, known as the Smart Hydrogen Sensor (SHS) was developed to acquire and process data from the hydrogen sensor, temperature sensor, and pressure sensor. The system configuration is shown in Fig. 3.

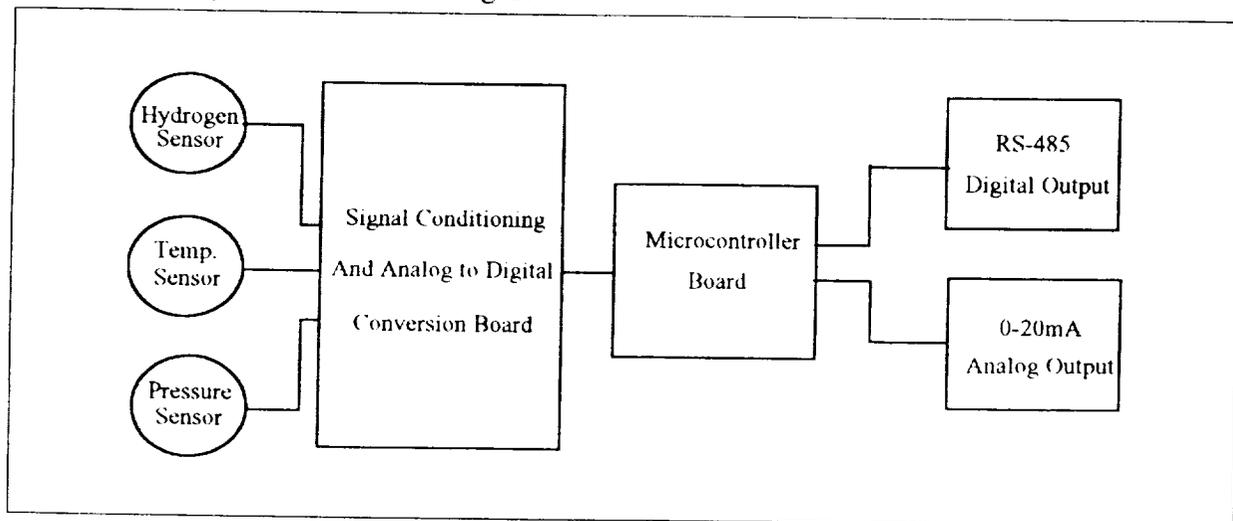


Figure 3. Smart Hydrogen Sensor Hardware Configuration

The approach chosen for the development of the SHS hardware was to use proven, off-the-shelf components. This approach eliminated the need to design new hardware and minimized testing requirements.

The SHS is comprised of three pieces of integrated electronics components. The hardware components are:

- (1) Microcontroller Board
- (2) Signal Conditioning Board (designed at Stennis Space Center)
- (3) RS232C/0-20mA Converter.

Microcontroller Board

The Microcontroller Board is built around an eight-bit microprocessor. It provides three 8-bit parallel I/O ports (24 bits), two asynchronous serial ports (one full-duplex RS-232, one half-duplex RS-485), eight-channel analog-to-digital converter (10-bit resolution at five volts), 96 kb of total on-board memory (EPROM and RAM), and 1024 bits (64 bytes x 16 bits) of EPROM.

As implemented with the SHS, the Microcontroller Board uses a ROM monitor and a multitasking BASIC compiler. Software development was carried out directly on the Microcontroller Board. The board interfaces directly to the Signal Conditioning Board.

Signal Conditioning Board

The Signal Conditioning Board, designed at Stennis Space Center, rides piggy back on the Microcontroller Board. The primary purpose of this board is to (1) convert input power to appropriate levels needed by the SHS unit and (2) condition the signals from the hydrogen, pressure, and temperature sensors prior to the digital conversion by the microcontroller.

The signal conditioning board also features a Computer Operating Properly (COP) Watchdog timer and an eight pole switch (dual-in-line package). The eight pole switch is used to (1) configure the SHS unit for the RS485 network and (2) place the sensor in either NORMAL or CALIBRATION operating mode.

RS-232/0-20mA Converter

The RS232/0-20mA Converter provides a direct means for outputting an analog signal from the SHS unit. The converter uses simple ASCII commands to control a 12-bit digital-to-analog converter. An on board microprocessor provides the communications interface. The RS232/0-20mA Converter receives the ASCII commands from the Microcontroller Board's RS232 serial port.

Software Description

The SHS software, written in a special version of BASIC which is unique to the Microcontroller Board, resides as firmware in EPROM. Although this microcontroller BASIC utilizes commands not standard to BASIC, modifications to the software are relatively simple with an understanding of standard BASIC commands and programming practices.

The main purpose of the firmware is to acquire temperature, pressure, and hydrogen data and use this data to estimate the concentration of hydrogen in the environment. This estimate is updated every second and is sent out to a 0-20mA analog channel. Furthermore, the firmware is responsible for monitoring communications over the RS485 network. If the SHS receives a valid command or request, it is responsible for responding with an appropriate reply.

Testing and Performance

Several iterations of prototype development and tests were completed before arriving at a software and hardware configuration deemed ready for operations in the NASA environment. The prototypes were tested in Stennis' laboratories over a wide range of temperatures and were exposed to a variety of background gases and hydrogen concentrations. Sensors were placed in some of the most severe operational environments imaginable, including the rigors of actual rocket engine firings, and were exposed to cryogenic fluids, saturated oxygen vapors, and heavy water deluge sprays.

Final testing results showed the sensor response to environmental changes was more linear with actual response time increased by a factor of 10. For comparison, sensor response time at 68° F to a 90% step change in H₂ concentration without use of the predictive algorithm was 1.5 minutes. Response time with the predictive method was significantly shortened to 8.5 seconds.

Additional software added to the system enables menu-driven operation, calibration and maintenance of the system's computer which reduces maintenance cost and ensures uniformity in system operations. Benefits of the Smart Hydrogen Sensor are: 1) speed of response, 2) accuracy, 3) reliability, 4) ruggedness, 5) ease of operation, and 6) flexibility.

APPLICATION STUDY - SMART THERMOMETER FEASIBILITY

With the successful application of the predictive hydrogen detection system, it followed that slow responding commercial measurement systems might benefit from this development. Further investigations were thus initiated to determine if the Smart Hydrogen Sensor technology could be readily applied to similar technological difficulties within the commercial sector. To determine viability, a test was developed using a leading brand medical-type electronic thermometer mated with the SHS signal processing hardware and software.

Hardware and Software Design and Assembly

Testing of the commercial thermometer system showed the normal response time to be between 25 and 30 seconds. Since the analog signal of the probe was different from the hydrogen sensor, a custom analog signal conversion circuit was designed and fabricated. The probe and custom circuit were then interfaced with an SHS programmable microcontroller and digital to analog converter. The microcontroller's BASIC software used for the SHS predictive algorithm was modified to process the temperature data from the thermometer probe.

Upon successful test of the software, the analog and digital electronics were assembled and calibrated using a precision calibration water bath. The method is similar to the ASTM standard for calibration of electronic medical thermometers.

Preliminary Test and Evaluation

Since medical practice requires the use of plastic sleeves on the thermometer probe for sanitary purposes, a problem was foreseen with the predictive method in that the individual probe covers could randomly alter the time constant of the temperature measurement assembly. To test the breadboard system and the variable time constant hypothesis, a series of temperature measurements were taken in a controlled temperature bath using different probe covers. Final temperature results obtained with different probe covers were found to be invariable, but, the time of response to reach the final temperature was found to vary by several seconds. The variation in response time necessitated the entry of a new time constant in the software to obtain an accurate prediction of the final temperature. The predictive method would be problematic in a medical application where accuracy is critical without an accurate value for the probe/temperature probe assembly time constant.

Modification of Predictive Method

A concept was therefore developed for solving for a unique time constant of the assembly "on-the-fly" by analyzing the first few seconds of measurement data. The method was developed using the data available from controlled temperature bath experiments. While these predictions from controlled experiments yielded promising results, viability under "clinical" conditions remained in question. Further investigations were then conducted using temperature data from volunteers in the laboratory. Three to four measurements were obtained from each volunteer using a different probe cover for each measurement. Selected data representative of the testing is discussed below.

Results

The data provided in Fig. 4 below shows the raw output of the temperature probe, the standard predictive method (as employed by the SHS), and the modified predictive method. For Fig. 4, the probe was inserted approximately 3 to 4 seconds after starting data acquisition. As can be seen, the standard prediction reaches the final temperature value within approximately 1 second. However, the standard prediction increases above the actual measured condition as a result of an error in the time constant assumed for the probe cover / temperature probe assembly used. This effect may be the result of minor differences in the probe cover or in the way the probe cover is attached to the probe.

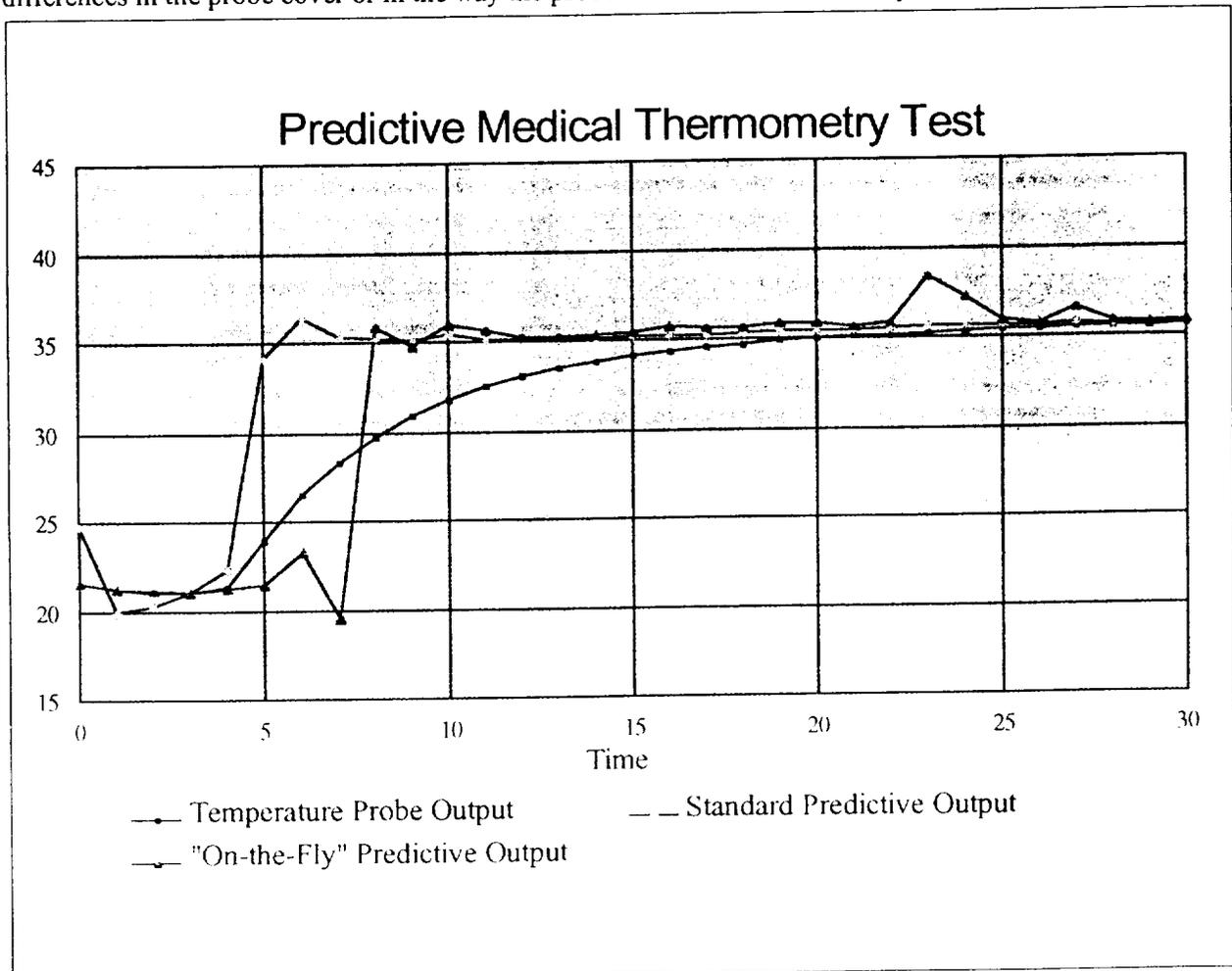


Figure 4. Test of Predictive Method in Medical Thermometry Application

The "on-the-fly" prediction uses temperature data from the first few seconds to calculate a time constant value unique to the probe in use. As seen in Fig. 4, this procedure produces a initial lag until the microcontroller has accumulated sufficient data to compute the time constant and final value, based on the "on-the-fly" time constant.

While a technique was implemented to solve the unique time constant problem associated with the probe covers, the data indicate that the technique does not improve the predictive results as it is highly sensitive to small nuances in the raw data. The use of thinner, more uniform, or more conductive probe covers might reduce the effect of differences in the manufactured probe covers on the time constant. This remains an area for further investigation.

More positively, the predictive method could prove beneficial for less critical applications such as household thermometers which require no sleeve covers. In such applications it is likely that the relationship between cost considerations and accuracy issues would shift, and more emphasis be placed on the design of a low cost chip and software.

PREDICTIVE SENSOR TECHNOLOGY APPLICATIONS

The Smart Hydrogen Sensor was developed to enhance the detection of hydrogen in a variety of gaseous atmospheres. The advanced electronics of the SHS system provide for reliable and rapid estimation of hydrogen concentration along with enough flexibility to function in a variety of environments. No commercial technology has been identified that can out perform the SHS in the areas of speed, accuracy, and reliability. The greatest attribute of this newly developed predictive sensor technology, however, is that it can significantly enhance the speed of response of existing sensor technology. Faster responses can be obtained without developing a faster sensor. Application of the predictive methodology may provide cost effective alternatives for existing sensors that are limited by slow response times. The signal processing algorithm employed can determine in near real time the steady state response of a normally slow sensor.

While a few shortcomings in its use in temperature measurement for critical medical applications remain to be resolved, the technology is readily applicable and adaptable to other types of temperature measurement systems.